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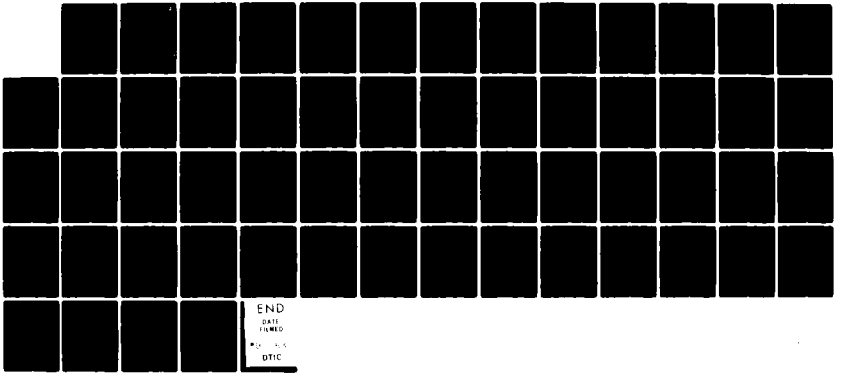

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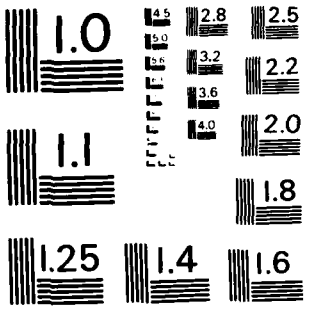

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Geomagnetic Pulsations-Production / Interpretation

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Elwood Maple

The Trustees of Emmanuel College
400 The Fenway
Boston MA 02115

September 1982

Final Scientific Report

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Amplitude Bursts
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Hydromagnetic Resonance
Input Bursts
Magnetometer Network
Middle Latitude
Plasmasphere
Polarization Traces
Resonance Mechanisms

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I. INTRODUCTION

The work under Grant No. AFOSR 77-3467 during the period 1 September 1977 to 30 September 1981 has been devoted to experimental studies of middle-latitude geomagnetic pulsations in the period range 0.2 to 50 minutes. The principal effort has been on the resonant periods of the pulsations which arise from hydromagnetic resonances in the magnetosphere. The resonant periods appear as peaks in the period distributions and frequency spectra of the pulsations.

Many papers, both experimental and theoretical, have been published on this subject over the past thirty years by a number of different investigators. Holmberg (1951) first suggested hydromagnetic resonance as a source of the pulsations to account for the peaks at about 20 and 70 seconds in the period distributions of pulsations recorded at Eskdalemuir, Scotland. In the pre-satellite era, the resonances were attributed to the ionosphere. Resonance along magnetic field lines has since become the favored hypothesis to explain the quasi-sinusoidal waveforms often observed. The theory was first applied to the ionosphere (Kato and Watanabe, 1955) and then to the magnetosphere (Obayashi and Jacobs, 1958). The polarization of pulsations observed simultaneously at geomagnetic conjugate points provided the first conclusive evidence for a magnetospheric source of the pulsations (Sugiura, 1961). Many later observations have confirmed the existence of standing waves in the magnetosphere, and magnetospheric resonance has become firmly established as a major source of the pulsations. The nature of the resonant mechanism, however, has been much less certain.

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Chief, Technical Information Division

A harmonic series of resonant periods is predicted by the field-line-resonance hypothesis which is the only physical mechanism that has been proposed up to the present time. The observational data that have accumulated over the years have been inconclusive; there has been some supportive evidence and some contradictory evidence. Of the studies that have been unfavorable, none has covered a wide enough period range to present a recognizable pattern of resonant periods as an alternative to the harmonic series. Under these conditions, the field-line-resonance hypothesis has become firmly entrenched, and its acceptance has become self-reinforcing. Published data that have not supported the hypothesis have been ignored or forgotten, and more recent observational data have been examined only in the light of the hypothesis. Some data that have not supported the hypothesis have been discarded without publication and without any serious attempt to determine whether they might furnish any definitely contradictory evidence.

The resonant periods of the pulsations analyzed under this grant have consistently formed geometric progressions in the period range 0.2 to 6 minutes. Two nighttime data samples recorded during large magnetic disturbances and two daytime samples recorded during low to moderate disturbance levels have been analyzed. The results are sufficiently comprehensive to be in clear-cut disagreement with a harmonic series of resonant periods. No theoretical explanation for the geometric progressions has yet been devised. It is clear, however, that the field-line-resonance hypothesis cannot, at present, be considered to be established as

the explanation for the magnetospheric resonances observed at middle latitudes.

The present work utilizes "polarization traces" which provide continuous displays of the polarization of the pulsations in selected period bands. This analysis technique was conceived some time ago. The early studies established that hydromagnetic (HM) waves were frequently observed throughout the 0.2 to 50 minute period range and that waves of several different periods were often observed simultaneously during both magnetically quiet and disturbed intervals,(Maple and Frey, 1967; Frey, 1969). That effort was terminated before the potentialities of the technique had been exploited, and the early results were not widely disseminated. Some of the original data have been resurrected for the initial work under this grant, and the analysis technique has been extended.

II. THE DATA OF 18 APRIL 1965

The 12-hour data sample (0000 to 1200 EST) was recorded at Strawberry Hill, Mass., geomagnetic latitude $+54^{\circ}$. Three components of the pulsations (north-south, east-west, and vertical) were recorded on 7-track, f-m tape. The induction coil sensors used provided a linear response in $\partial B/\partial t$ throughout the period range of interest. The interval 0000 to 0600 EST during the large magnetic storm of 18 April 1965 (maximum Kp = 8-) was one of the "auroral-oval intervals" (A-O intervals) identified by Maple et al.

(1975) when the Strawberry Hill station was inside the southern boundary of the expanded auroral oval. The large-amplitude A-O regime of pulsations observed during the A-O intervals was distinguished from the "mid-latitude" (M-L) regime of pulsations usually observed at the station. The conditions during the interval from 0600 to 1200 EST were not typical of the M-L regime, however, since the station would have remained outside the plasmapause during the slow refilling and expansion of the plasmasphere after the storm.

II. A. SELECTION OF FILTER PASSBANDS

The first evidence of the natural band structure of the pulsations came from observations of bandpass-filtered waveforms. The original broad-bandwidth analog tape recordings consisted of a linear superposition of many short wavetrains whose periods covered a very wide range. The superpositions were quite prominent in the $\partial B/\partial t$ recordings because the differentiation emphasized the shorter periods and thus partially compensated for the increase in pulsation amplitudes with increasing period. The initial intent was to study the polarization of the pulsations, and filter passbands about one octave wide were to be used to effect a partial separation of the individual wavetrains for this purpose. It was soon found that there were some preferred settings of the center period of the passband for which very few cases of superposition of concurrent wavetrains were observed in the filtered

waveforms. When the center period of the passband was shifted away from one of the preferred settings by about a quarter of an octave (toward longer periods, for example), additional (longer period) wavetrains would appear superposed on the wavetrains that had previously been present. As the center period was shifted further in successive steps, the new (longer period) wavetrains would become predominant, and a new preferred setting would be reached for which the new wavetrains would be observed with very few cases of superposition of the previous (shorter period) set of wavetrains.

The filter passbands to be used for the polarization analysis were therefore matched to the natural band structure indicated by the preferred center periods. The nine selected passbands cover the period range 0.2 to 50 minutes. They are numbered A1 through A9 in Figures 1a and 1b, and their nominal cut-off periods are shown by the C's at the bottom of the plots. (The other features of these plots will be discussed later.) The minimum widths of the passbands were constrained by the requirement that adjacent passbands should share a common nominal cut-off period. Good coverage of the entire period range was thus ensured. At the nominal cut-off periods (i.e., the periods read from the dials of the Kron-Hite variable-bandpass filters), the filter response curves had dropped only 20% below their peak values. At their half-power points, the passbands were appreciably wider, and adjacent passbands overlapped. The nine passbands cover a period range of more than seven octaves, and the narrowest bandwidth is more

than half an octave in width. The superposition of wavetrains was not completely eliminated in these comparatively wide passbands, but it was greatly reduced by the selection process. The number of superpositions of concurrent wavetrains of different periods was much smaller in Bands A7 and A6, for example, than in an intermediate (non-selected) passband of comparable width whose cut-off periods would correspond to the center periods of Bands A7 and A6. A similar statement would apply to each pair of adjacent bands, although the observations were less clear-cut for Bands A1, A2, and A3 for which comparatively few pulsation cycles were available for observation. Any significant shifts of the center periods of the selected passbands produced increases in the number of superpositions of wavetrains which were observed. Period distributions peaking near the centers of the passbands were implicit in the observations, therefore, even before the distributions were actually derived from the later analysis.

The selected filter passbands formed a fairly regular sequence with the ratio of adjacent center periods being a little less than two. Spot checks of the ratios of the periods of the pairs of superposed wavetrains which were commonly observed in intermediate (non-selected) passbands showed that the most common value of this ratio was also a little less than two. The only possible explanation for these results was a regular band structure in the pulsations such as would be produced by a series of low-Q magnetospheric resonances. When excited by a broad-bandwidth energy source, the output of each resonance would consist of a series of wavetrains in a band centered at the resonant period, the width

of the band being determined by the Q of the resonant mechanism. While the output of a narrow filter bandwidth centered on one of the resonant periods would show only one pulsation wavetrain at any given time, the bandwidths selected for the analysis, whose widths were comparable to the spacing between the resonant periods, would sometimes include wavetrains associated with one of the adjacent resonances. A passband centered between two of the resonant periods would frequently show superpositions of pairs of concurrent wavetrains, one from each of the two resonances.

II. B. POLARIZATION TRACES

Plots called "polarization traces" which displayed the polarization of the pulsations in the horizontal plane were used to identify the individual wavetrains which constitute the filtered waveforms. The X and Y components of the pulsations were processed simultaneously with identical settings of Kron-Hite variable-bandpass filters and identical simple, low-pass RC circuits which provided integration in the period range of the filter passband. The integrated and filtered waveforms, which then displayed time variations of B rather than the $\partial B/\partial t$ originally obtained from the induction coil sensors, were recorded on 7-track f-m tape along with a time track and calibration information from the original tape. The waveforms for the nine selected passbands were processed on an analog computer which produced the polarization traces. For detailed analysis, it was then necessary to punch the results on cards for processing on a digital computer.

A section of a polarization trace is shown in Figure 2. (The example is taken from the data of 2 May 1978 which will be discussed later. This trace is more regular than those derived from the wider filter passbands used for the 18 April 1965 data.) The azimuth angle of the magnetic vector in the horizontal plane is computed from the instantaneous values of the X and Y components of the filtered waveforms, and the cumulative azimuth angle is plotted in 90° steps as a function of time. The numbers on the ordinate of the plot are complete 360° rotations of the vector. Each vertical step shows the time when the vector changed quadrants; that is, when it passed through 90°, 180°, 270°, or 360°. The horizontal steps then show the times that the vector spent in each quadrant. For a sinusoidal wavetrain, the center points of the horizontal steps would lie on a straight line whose slope would give the period of the wave. When straight lines are fitted to the center points by the least-squares method, the RMS deviations of the points provide measures of the regularity of the waveforms which produced the trace. Each portion of the trace which has a minumum length of one complete 360° rotation of the vector and yields an RMS deviation less than a predetermined value is called a "polarization run". The computer provides the period and the duration of each run which identifies one of the many short wavetrains that constitute the filtered waveforms. The terms wavetrain and polarization run (or simply run) are used synonymously hereafter, and the length of the wavetrain may be expressed either by the number of pulsation cycles or by the number of rotations of the magnetic vector. Four polarization runs

are indicated in Figure 2, and one of the fitted straight lines is shown. The first three runs have a positive polarization which produces an increase in the number of rotations and indicates a clockwise rotation of the magnetic vector looking downward along the positive direction of the field lines. The fourth run, at the right, has a negative or counter-clockwise sense of polarization.

In previous studies, pulsation periods have been derived from single-component recordings. In some cases, average periods for selected time intervals have been used, but this eliminates much of the detail needed to form period distributions. In other cases, individual wavetrains have been selected by inspection. Comparisons of the X, Y, and H waveforms (see later discussion) indicates that the H waveforms and the polarization trace, which also combines the X and Y components, provide a better basis for the selection of the individual wavetrains than either the X or Y component taken alone. The computer scaling of the trace also makes the selection an objective one.

Polarization traces for the nine selected passbands are shown in Figure 3 (nominal filter cut-off periods as shown). The traces provide legible displays of the polarization of the pulsations over extended intervals of time. The strong positive or negative trends persisting for a number of cycles in many sections of the traces provide convincing evidence for HM wave activity as the source of a large percentage of the pulsations throughout the period range.

The compressed time scale of Figure 3 causes an increasing loss of detail in the traces as the pulsation periods decrease. Each trace is composed of many polarization runs. Considering

all runs having lengths of one rotation or more of the magnetic vector ($R \geq 1.0$), the total number of runs ranges from 8 for Band A1, which has an average pulsation period of 41 minutes, to 920 for Band A3 with an average period of 0.33 minutes. For the nine bands, the average length of the runs was 2 rotations, and the average total polarization (i.e., the combined time durations of the runs) was 82% of the length of the polarization trace. Of the total polarization, 44% was accounted for by runs having lengths in the range $2.0 \leq R < 4.0$, 16% by runs with $R \geq 4.0$, and 38% by runs with $R < 2.0$. The short runs ($R < 2.0$) provide important contributions to the strong clockwise or counter-clockwise trends of the polarization traces which were noted above. Thus the short runs (or at least a large percentage of them), as well as the longer runs, are attributed to EMI wave activity.

The statistics of the polarization were essentially the same during the A-O interval from 0000 to 0600 EST as for the following M-L interval from 0600 to 1200 EST. There were no appreciable differences in the average length of the runs or the percentage of time occupied by the combined durations of the runs during the two intervals with only one exception. For Band A3, the average run length was 1.9 rotations for the A-O interval and 2.9 rotations for the M-L interval.

The strong clockwise trend for Bands A8 and A9 (periods shorter than 40 seconds) during the A-O interval is opposite to the predominant counter-clockwise trend observed for this period range at Strawberry Hill in the early morning hours for the less-disturbed M-L regime. Samson et al. (1971) and Samson and Rostoker (1972) show that the sense of polarization reverses from clockwise at high latitudes to counter-clockwise at lower latitudes during the morning hours and that the latitude of the reversal decreases with decreasing pulsation period. Their Pc3 polarization reversed at about 60° geomagnetic. During the A-O interval at Strawberry Hill, the latitude of the reversal had shifted southward with the auroral oval boundary to +54° or less. It is possible that the clockwise polarization in Band A7 just prior to 0400 EST is a similar effect. The predominant trend for Bands A1 through A6 (periods longer than 1 minute) is counter-clockwise in the morning hours in agreement with many previous reports.

A peak in pulsation amplitude at the latitude of the polarization reversal was noted in the papers cited above and has also been predicted theoretically (McClay, 1973; Radoski, 1974; Chen and Haserawa, 1974; Southwood, 1974). However, a peak in the amplitudes of the A-O pulsations in Bands A8 and A9 at the latitude of Strawberry Hill is not to be expected. Maple et al. (1976) noted that for any given level of magnetic disturbance, the amplitudes in this period range at Strawberry Hill were smaller than the corresponding amplitudes at College, Alaska, reported by Campbell and Matsushita (1962).

II. C. FILTERED WAVEFORMS AND POLARIZATION RUNS

The pulsation waveforms have been examined by marking off the times of all the polarization runs identified by the computer on stripchart records which included the filtered and integrated X, Y, and H ($=(X^2+Y^2)^{\frac{1}{2}}$) component waveforms along with a time trace. Band A9, which provides 920 runs for examination, is used for this discussion.

The succession of wavetrains that make up the waveforms are usually most clearly observed as short "amplitude bursts" in the H component. The occurrences of polarization runs having lengths of 2 to 4 rotations show a general agreement with the occurrences of the bursts, but there is not a one-to-one relationship. Runs longer that 4 rotations usually extend over 2 (or more) amplitude bursts. There are also some "gaps" between runs, i.e., sections of the polarization trace that do not meet the criteria for runs.

There are no very long gaps. For Band A9, no gap is longer than 2 minutes, and only 4 are longer than 1 minute. Of the 429 gaps, 278 (65%) have durations of less than 0.3 minutes; i.e., less than the average pulsation period for the band.

When comparatively isolated amplitude bursts occur, their durations are seldom longer than about 3 cycles. The amplitude of a typical isolated burst first increases and then decays; the initiation of the burst is not impulsive. The occurrences of successive amplitude bursts is quite irregular, and there is no indication of the "beating" which would occur if two closely spaced frequencies were present. The independence of successive bursts is often indicated by appreciable differences (10% or more) between the periods of successive runs and by the fact that successive runs may have either the same or opposite senses of polarization.

Successive amplitude bursts are not usually isolated from each other. In some cases, the start of a new polarization run clearly coincides with the beginning of a new burst which appears before the previous burst has decayed; the new burst becomes dominant after an irregularity in the waveforms which may, or may not, cause a short gap between the end of one run and the start of the next. In other cases, there is no clear occurrence of a new burst at the start of a new run, but merely an irregularity in one or both of the X and Y waveforms. Polarization runs less than 2 rotations in length show a tendency to be associated with small X and/or Y amplitudes.

The waveforms observed in each filter passband are consistent with the output to be expected from a low-Q resonant mechanism excited by a variable, broad-bandwidth source of energy. The polarization runs are produced by a series of independent excitations of the mechanisms by "input bursts" corresponding to the "amplitude bursts" in the H component waveforms. The simplest input bursts would be bursts of energy whose spectra peaked at different frequencies in the passband to account for the varying periods of the runs. Comparatively large shifts in the peak of the frequency spectrum of the source without pronounced changes in input energy could produce somewhat similar results. Sharply peaked spectra for the input bursts are not required to produce the observed output waveforms.

The interval between the initiations of successive input bursts is variable and averages about 2 pulsation cycles (i.e., the average length of the polarization runs). An isolated burst produces a buildup of energy in the resonant mechanism which decays when the input ceases or decreases in amplitude. For a low-Q mechanism, both the buildup and decay can occur rapidly within one or two cycles of the output waveform. Interaction between successive input bursts occurs when the new burst is initiated before the energy stored in the mechanism during the previous burst has been completely dissipated. Irregularities in the waveforms caused by the interactions would often produce the short "gaps" frequently observed between successive runs. Many of the runs would therefore be shorter than the interval between

successive input bursts. The short runs tend to be associated with small waveform amplitudes and are thus likely to have been shortened by the interactions.

The examination of waveforms again indicates that the short runs ($R < 3.0$) are produced by the same physical mechanism that produces the longer runs.

II. D. PERIOD DISTRIBUTIONS

The histograms of Figures 1a and 1b show the period distributions of the pulsation wavetrains observed in the nine selected filter passbands. The period range 0.21 to 50 minutes has been divided into equal intervals on a logarithmic scale (logarithmic increment = 1.111), and the number of cycles in the wavetrains in each period interval have been summed. The number of cycles in each interval has been divided by two to provide numbers comparable to the actual number of runs. The resulting numbers are plotted and labelled "weighted occurrences of polarization runs" in the figures. The number of runs diminishes with increasing period as the number of pulsation cycles which could be observed in the fixed time interval decreases. The plots for Bands A5 and A4 are repeated in Figure 1b with an expanded ordinate scale to provide continuity.

In Figure 1a, the arrows numbered 1 through 6 indicate a set of periods which form a geometric progression with the value of R, the common ratio of adjacent periods, being 1.7. The median periods of the distributions agree with the periods of the progression to within $\pm 4\%$. The R value is critical; the agreement

with the data deteriorates rapidly when R is varied by more than 1%. In Figure 1b, the arrows below Bands A3 through A1 indicate the median periods of those distributions. The ratio of the median periods of Bands A4 and A3 is 2.4, and it is clear that Band A3 is not a continuation of the progression.

Bands A3 through A4 are thus interpreted as a geometric progression of six low-Q magnetospheric resonances with a fundamental period of about 5 minutes and an R value of 1.7.

All polarization runs having $R \geq 1.0$ (i.e., having lengths of one complete 360° rotation or more of the magnetic vector) were used in the overlapping period distributions of Figures 1a and 1b. Period distributions for four categories of run length ($1.0 \leq R < 1.5$; $1.5 \leq R < 2.0$; $2.0 \leq R < 3.0$; and $R \geq 3.0$) have also been constructed. The shapes of the distributions for the four run lengths are quite similar, again indicating that the short runs ($R < 2.0$) are produced by the same physical mechanism as the longer runs. The periods of the short runs are less precisely difined and produce somewhat broader distributions.

Holmberg (1951) considered the resonance mechanisms as band-pass filters with a random noise input. The characteristics of the filter outputs (i.e., the pulsation waveforms) then yielded an estimate of 4 or 5 for the Q's of the resonances. On the same basis, the Q's of the resonances determine the shapes of the period distributions. When resonance curves for RLC circuits having various Q values were fitted to period distributions obtained for runs with $R \geq 2.0$, the curves computed for Q's of 5 had shapes similar to those of the distributions, in agreement

with the results of Holzberg. The half-power points of the resonance curves lay within the nominal cut-off periods of the bandpass filters used for the analysis, and the passbands of the filters measured at their half-power points were appreciably wider than the resonance curves. As previously noted, the response curves of the filters had dropped only 20% below their peak values at the nominal cut-off periods shown in Figure 1. The period distributions previously established by the magnetospheric resonances would not, therefore, have been appreciably altered by the bandpass filters. The RLC circuits were used for convenience in the calculation of the effects of energy dissipation, as measured by the Q value, on the response curves of simple resonant systems. The actual magnetospheric resonance mechanism, although physically different, would show similar effects.

The hourly period distributions for Bands A9 through A6 are usually, but not always, more sharply peaked than the overall distributions of Figure 1a. The median periods of the hourly distributions are within $\pm 6\%$ of those of Figure 1a with only 2 exceptions out of the 48 cases. The median periods of the different bands do not increase or decrease simultaneously, and the hourly values of the ratios of the median periods of adjacent bands can occasionally vary appreciably.

The one-hour intervals do not provide complete averaging of the short-term variations of the frequency spectrum of the energy source which excite the magnetospheric resonances and produce the varying periods in each band. Independent excitations of the

different resonance bands and a lack of close coupling between the bands account for the observed variability of the hourly period distributions.

The ratios of the periods of pairs of pulsation wavetrains that were linearly superposed in the original, unfiltered recordings have been examined by comparing pairs of partially concurrent wavetrains observed in adjacent pairs of filter passbands. A combined distribution of these ratios has been obtained for the four band pairs A9-A8, A8-A7, A7-A6, and A6-A5. In terms of the period intervals used in Figure 1a, the probability that a run in interval N is partially concurrent with another run in the period interval N $\pm$ i is tabulated below. The highest probability occurs for i = 5 corresponding to the spacing of the peaks in Figure 1a.

i =	1	2	3	4	5	6	7	8	9	10
P =	.01	.05	.12	.18	.21	.19	.13	.07	.03	.01

This is in agreement with the spot checks made during the selection of filter passbands and confirms the geometric progression of resonance bands. There is no evidence of a close relationship between the runs in adjacent bands. The two runs in a pair are only partially concurrent, and the amount of overlap is quite variable. Also, the two runs may have either the same sense or opposite senses of polarization.

Most of the observed features of the data can be attributed to essentially random variations of the energy source which excites the magnetospheric resonances. This simple model does not, however, account for the strong clockwise or counter-clockwise trends shown by many sections of the polarization traces of Figure 3.

It is again emphasized that the observed distributions are statistical in nature. A single set, or even several sets, of partially concurrent low-Q wavetrains would not necessarily provide reliable estimates of the median periods of the resonance bands or of the ratios of the median periods of the different bands.

II. E. OTHER RESULTS OF THE ANALYSIS

The amplitudes of the pulsations peaked in the interval 0100 to 0300 EST during the height of the magnetic storm when the Kp index reached a maximum of 8-. The maximum hourly average amplitudes of the H component ranged from 35 gammas for Band A1 to 0.73 gammas for Band A9. The amplitudes dropped thereafter, particularly after 0600 EST when the southern boundary of the contracting auroral oval receded northward from the station. By the hour 1100 to 1200 EST, the amplitudes had dropped to 3 gammas for Band A1 and 0.02 gammas for Band A9.

Strong cosmic noise absorption (6 db maximum) was recorded on the 22 MHz riometer at Bedford, Mass., from 0100 to 0300 EST, and the smoothed CNA curve was very similar in shape to the envelope of the pulsations having periods of 1 minute and less. The peaks of the small variations superposed on the envelope of the CNA curve were correlated with the positive peaks (corresponding to northward-directed fields) of the filtered and integrated X component waveform of the pulsations in a 5.5 to 17 minute passband. The increases in particle precipitation that

caused the increases in CNA might also have been expected to cause increases in ionospheric conductivity accompanied by increases in the strength of the westward-flowing electrojet, but this would have produced increases in the southward-directed field in disagreement with the observations. The relationship between the CNA and the pulsations must therefore be attributed to a common origin in the magnetosphere.

All of the evidence indicates that 80% or more of the pulsations are of magnetospheric origin throughout the measurement interval. The magnetic variations in the 0.26 to 50 minute period range more directly associated with fluctuations of the auroral electrojet during the A-C interval must have been appreciably smaller than the concurrent, large-amplitude HM wave activity, since they did not reduce the amount of elliptical polarization below that observed during the following M-L interval when only the weak, slowly-varying Sq currents were overhead. During the A-O interval, the fields of the HM waves were not negligible in comparison with the electrojet. The electrojet field as shown by the H component on the magnetogram at the Weston, Mass., observatory reached a maximum value of about -750 gammas or about 8 times the maximum peak-to-peak amplitude of the pulsations in Band A1.

II. F. COMPARISON WITH PREVIOUS RESULTS

Additional observational data will be presented prior to the comparison with previous results relevant to the subject of magnetospheric resonances.

II. G. SUBMISSION TO THE JOURNAL OF GEOPHYSICAL RESEARCH

A paper describing the initial results obtained under the Grant was rejected by the Journal of Geophysical Research. The remarks of the referees indicate that any challenge to the field-line-resonance hypothesis was regarded as heresy which should be firmly suppressed.

The Brand X Referee (BXR) stated that "The technique eventually reverted to the use of the human eye in deciding when the filter width has been decreased to the point where only a single frequency is present."

Since the overlapping filter bandwidths provided complete coverage of the period range, a single frequency per filter bandwidth would be compatible with the stated results of the analysis but would be incompatible with the harmonic series of frequencies predicted by the field-line-resonance hypothesis. The BXR's misstatement of the analysis technique could hardly be considered a devastating criticism, even if it had been true.

The remaining comment of the BXR concerned the RLC circuits which were used only in estimating the Q's of the resonances and were not used as physical models of the magnetospheric resonance mechanisms. The BXR complained that the RLC circuits were not physical models of the magnetospheric resonance mechanisms.

The Brand Y Referee (BYR) stated "This is actually what the author did by his 'cumulative area' technique of counting rotations and defining 'runs'."

The BYR's remark was clearly intended to refer to the polarization traces, but the traces did not involve cumulative areas

in any way. This confusion on the part of the BYR concerning the contents of the paper he was refereeing was quite extensive.

The BYR stated "I understand that the author has normalized the distributions of rotations in each filter band. However, he does not describe how this was done so I can't validate it." And later he stated "Clearly there is some frequency signal which is attenuated by the filter to the noise level of the electronics. This signal will not be detected by the rotation analysis. No amount of normalization can compensate for this loss. I am not convinced that the statistics were properly normalized, or that it is possible to do so."

The only normalizing done consisted of setting the maximum amplitudes of some of the secondary plots (not shown in this report) equal to one. This simple procedure apparently caused the BYR to conjure up some esoteric normalization scheme. As intended, the bandpass filters attenuated the signals outside their passbands. There was no desire to detect or compensate for the intentionally discarded signals.

Further comments by the BYR: "I also understand the check he has made by moving a wide band filter across a narrow spectral line, observing that the output period moves across the band in the appropriate manner." And later: "At a deeper level I am concerned about the use of narrow band filters and polarization analysis to estimate the spectrum of a signal which is what the author has done."

The check that the BYR "understands" is unknown to the author. The spectral lines observed were not narrow, even though

they were not as wide as the filter bandwidths. The BYR uses the designations "wide band" and "narrow band" interchangeably in referring to the filters.

At a deeper level, the BYR is concerned about the use of period distributions in the analysis of the pulsations even though this technique has been used in many papers that have been published in the JGR and elsewhere without evoking any great consternation.

I have been assured by the Editor that the Brand X and Brand Y Referee "were selected for their expertise on the subject matter of the paper." Since many authors have encountered similar uses of "expertise", it seemed worthwhile to document one example.

III. A. ADDITIONAL DATA ANALYSIS

Three additional data samples selected from the archives of the Air Force Geophysics Laboratory's Magnetometer Network have been analyzed to confirm the results of the initial analysis. The data were recorded at the Mt. Clemens, Michigan, and Rapid City, South Dakota, stations in the northern tier of the network at a geomagnetic latitude of about $+54^{\circ}$, L value of about 3, approximately the same as that of the Strawberry Hill station. The outputs from the induction coil sensors had been digitized at a rate of 300 points per minute.

One data sample was recorded near local midnight during a large magnetic disturbance (Kp = 7o) so that conditions were similar to those for the 18 April 1965 data. That is, the station was outside the plasmapause and inside the southern boundary of the expanded auroral oval. The other two data samples were recorded during the early afternoon hours under conditions of moderate magnetic disturbance when the station was inside the plasmapause.

Consideration was given to practicable modifications of the analysis technique which might make it more difficult for determined skeptics to deprecate the results. Unfortunately, the comments of the Brand X and Brand Y referees of the JGR provided very little assistance in this regard. It was decided -- reluctantly -- to abandon the preselection of the filter passbands to be used for analysis. It was the observations made during the preselection process that first revealed the unexpected geometric

progression of the resonant periods of the pulsations. Although qualitative in nature, the observations were quite clear and were subsequently borne out by the period distributions. The JGR referees, however, simply ignored the significance of those early observations. Since there was no practicable way to present the observations other than the verbal description that had already been used, it seemed best to drop the preselection of passbands.

In the later analysis of data, therefore, a large number of narrow filter passbands have been used to cover the desired period range. This approach required more effort and computer time. It had the additional advantage, however, that it provided plots of the amplitudes of the pulsations as a function of frequency for comparison with the period distributions. The average amplitudes in the individual passbands provide enough points to define a smooth curve.

III. B. THE DATA OF 2 MAY 1978

Data from the Mt. Clemens, Michigan, station of the Air Force Geophysics Laboratory for the three-hour interval 0000 to 0300 CST on 2 May 1978 have been analyzed. The Kp index for the interval was 7o. The period range from 0.2 to 6 minutes has been covered by a series of narrow, overlapping filter passbands. Polarization traces for each passband were obtained as described in Section II. B. above; a section of one of the traces was shown in Figure 2. The period distributions for six of the overlapping filter passbands are shown in the upper plots of Figure 4. The period intervals are the same as those previously used in Figures 1a and 1b. The dotted curves are the response curves of digital

filters which have been adjusted to maintain a constant shape on the logarithmic period scale (i.e., to maintain a constant Q). The histograms are constructed from the sums of the time durations of the individual pulsation wavetrains identified from the polarization traces (rather than from the number of rotations of the magnetic vector used in the previous analysis).

Because the filter passbands were not pre-selected to minimize the superposition problem, the initial results obtained with wider passbands were sometimes ambiguous. Passbands covering four of the period intervals used in the plots of Figure 4 were first tried. The logarithmic increment of the intervals was 1.111 so that the ratio of the maximum and minimum periods in the four-interval span was 1.111^4 or 1.523, a ratio large enough to provide the possibility of the inclusion of many pairs of superposed wavetrains. When the center period of the comparatively wide passband was shifted in steps of one period interval, the resulting overlapping period distributions were not always consistent among themselves. Passbands covering three period intervals yielded better, but still not satisfactory, results. The ratio of the maximum and minimum periods in the two period intervals covered by the passbands of Figure 4 is only 1.234, which permits very few occurrences of superposed wavetrains. These narrow passbands clearly display the peaks in the period distributions. As expected, the ambiguities which had previously been observed were most pronounced in the regions between the peaks where the wider passbands would include concurrent wavetrains from each of the two adjacent resonance bands.

Each distribution in Figure 4 has been normalized by setting its maximum amplitude equal to one. The important features of each plot are the relative amplitudes in the two central period intervals for which the filter attenuations are small and equal. The total time duration of the wavetrains observed in each passband was about 75% of the duration of the data sample. However, the amplitudes of the distributions prior to normalization are not of great significance in this case because the narrow passbands impose a more sinusoidal appearance on many of the wavetrains than they would otherwise have.

The two overlapping passbands containing one of the peaks of the overall period distribution have been chosen for the plots on the two top lines of Figure 4. The two distributions peak in the same period interval. The third and fourth lines of the figure extend the period range, and in each case the period distributions continue to drop off from the central peak. The composite distribution shown in the lower plot is based on the relative amplitudes in the two period intervals of the individual passbands. Starting from the central peak, if each of the three passbands had shown a decrease of 20%, for example, the amplitudes in the composite distribution would be plotted as 1.00, 0.80, 0.64, and 0.51.

Figure 5 presents the results of the analysis of the three-hour interval. The average amplitudes of the $\partial H/\partial t$ component of the pulsations, derived from the filtered $\partial X/\partial t$ and $\partial Y/\partial t$ outputs of the induction-coil sensors, are shown in the upper plot. Each

point on the curve corresponds to one of the bandpass filters used in the analysis. In the period distribution, shown in the lower plot, each of the four peaks was derived independently as illustrated in Figure 4. The dashed vertical lines numbered 1 through 4 are equally spaced on the logarithmic period scale and form a geometric progression with a common ratio R = 1.84. The geometric progression provides a good fit to four peaks in both the amplitudes and the period distribution of the pulsations in the 0.3 to 3 minute period range. Outside that range, the pulsations do not conform to the progression. A secondary peak in the period distribution at about 0.27 minutes can also be seen in the amplitude curve. The peak in the amplitude curve at about 3.5 minutes is barely discernable in the period distribution.

It should be noted that the slow decrease in the amplitudes of the pulsations with increasing period results from the use of $\partial H/\partial t$ for the plot. A plot of H would show the usual increase in amplitude with increasing period.

The technique used in deriving the individually normalized peaks in the period distribution results in discontinuities between the peaks. No detailed investigation has been made, but the discontinuities are due in part to occurrences of the superposition of wavetrains of different periods. The narrow filter bandwidths restrict such occurrences to the troughs between pairs of peaks where wavetrains related to each of the two peaks are equally likely to occur. Small variations in the parameters of the analysis (i.e., filter bandwidths and the degree of regularity required for the selection of pulsation wavetrains) did not result in significant variations in the period distribution.

It was to be expected that the peaks in the period distribution would be more pronounced than those in the pulsation amplitudes. The smoothing effect of the overalpping filter bandwidths reduces the sharpness of the peaks in the amplitude curve. Also, each of the low-Q pulsation wavetrains contains energy spread over a comparatively wide frequency range. In the period distribution, however, all of this energy is attributed to a single period near the center of the range, and this sharpens any existing peaks in the distribution. The apparent periods of pulsations lying near the cut-off periods of the filters are shifted somewhat toward the centers of the passbands. For the comparatively narrow passbands used, this again tends to sharpen the observed peaks in the distribution.

III. C. THE DATA OF 15 JANUARY 1979

The results of the analysis of the three-hour interval from 1300 to 1600 CST on 15 January 1979 are shown in Figure 6. The data are from the induction coil sensors of the Rapid City, South Dakota, station of the Air Force Geophysics Laboratory, and the analysis procedure was the same as that described in the previous section.

The data were recorded during a moderate disturbance (Kp = 4o) and during the local afternoon hours when the station was well inside the inner magnetosphere, i.e., inside the plasmapause. The pulsation amplitudes are almost a factor of 10 lower than those in the previous data sample.

The dashed vertical lines again form a geometric progression. In this case, the common ratio R is 1.56. Four of the terms of

the progression, labeled 1, 2, 4, and 7, are in good agreement with the peaks in the amplitude curve and the period distribution. The other terms in the progression do not appear in the pulsation data, although there is a slight indication of a peak in the amplitude curve which corresponds to term 5 of the progression.

III. D. THE DATA OF 19 JANUARY 1979

The results for a second three-hour afternoon interval at the Rapid City, South Dakota, station are shown in Figure 7. The interval was rather quiet with a Kp of 2+, but the pulsation amplitudes for periods shorter than two minutes are larger than those for the previous data sample. The geometric progression shown by the dashed vertical lines again has a common ratio R of 1.56. In this case, only three of the terms in the progression appear clearly in the pulsation data, and the match for term 1 is not very good. There are also indications of peaks corresponding to terms 2, 3, and 6 of the progression.

Pulsation amplitude curves for six 15-minute intervals are shown in Figures 8 and 9. These examples were chosen to display the short-term variations which occurred during the three-hour interval. The common ratio R = 1.56 has been maintained for the progression, but the entire progression has been shifted slightly to provide the best fit for the individual cases. There is a general trend toward longer periods at later times. Changes in the common ratio were tried but did not improve the fit for the individual cases.

There are clear occurrences of peaks corresponding to each term of the progression in one or more of the 15-minute intervals with the exception of term number 5 for which there are only two

small indications of peaks. The fit to the progression is not always very good, but this is to be expected for low-Q resonances averaged over short time intervals. For a five minute period, for example, only three pulsation cycles could occur in fifteen minutes. There are also a few peaks in the pulsation amplitudes which cannot be identified with terms in the progression. These misfits are, however, far outnumbered by the peaks which do agree with the progression. A definite increase in the amplitudes of the longer-period pulsations occurs in the latter half of the three-hour interval.

III. E. OTHER DATA SAMPLES

Two other three-hour data samples have been examined, but in both cases large percentage variations of the pulsation amplitudes occurred rather randomly in both frequency and time, and no clear pattern could be discerned. In both cases there were some indications of a geometric progression of resonant periods, but the indications were not sufficient to warrant the presentation of the data here. In neither case could any indications of a harmonic series be observed. One of the data samples was recorded at night during a strong disturbance similar to that of the 2 May 1978 sample described in Section III. B. above. The other sample was recorded during the afternoon under very quiet conditions. The signal levels were very low and may have been contaminated with man-made noise.

IV. A. DISCUSSION

All four of the data samples presented show geometric progressions of the resonant periods of the pulsations. No interpretation in terms of harmonic series is possible.

All of the data samples were recorded at stations located at about $+54^{o}$ geomagnetic latitude, L value about 3. The field lines from the stations usually lie in the inner magnetosphere, i.e., inside the plasmapause. Near midnight, however, when the the Kp index reaches 7o or more, the stations are inside the southern boundary of the expanded auroral oval. Differences in the pulsations observed under these two conditions have previously been reported (Maple et al., 1976). Differences between the "mid-latitude" and "auroral-oval" regimes of pulsations at these sub-auroral-zone stations also appear in the data reported here.

IV. B. THE "AURORAL-OVAL" RESONANCES

The existence of a geometric progression of peaks in the data of 18 April 1965 (Figure 1a) was first inferred from qualitative observations of the filtered pulsation waveforms. Since it was those early observations that supplied the incentive for the remainder of the work reported here, it was fortunate that the "auroral-oval" regime of pulsations, for which the progression is quite clear-cut, was chosen to initiate the study of the polarization of the pulsations. The application of the modified analysis technique to the data of 2 May 1978 (Figure 5) verified the earlier results. The differing values of the common ratios and of the longest resonant periods of the two progressions

warrant further investigation. No comparable studies of the "auroral-oval" regime of pulsations are available for comparison.

IV. C. THE "MID-LATITUDE" RESONANCES

Holmberg (1951, 1953) presented an extensive analysis of the pulsations at Eskdalemuir, Scotland, +54.5° geomagnetic latitude. He found two prominent, distinct peaks in the period distributions of the pulsations. One peak was centered at a period of about 20 seconds, the second at 70 to 80 seconds. Holmberg noted the similarity of his results to those which might result if random noise were passed through low-Q filters and estimated the Q's to be about 4 or 5 from the pulsation waveforms. From a consideration of the characteristics of various possible physical mechanisms, he concluded that hydromagnetic resonance was the mechanism most likely to be capable of providing the observed period range. In the pre-satellite era, the ionosphere was assumed to be the seat of the resonances.

Peaks at about 20 seconds and 70 to 80 seconds have also been reported in the period distributions of the pulsations at Tucson (+40.4° geomagnetic) by Maple (1959) and at Fredericksburg (+50° geomagnetic) by Saito (1962). These two peaks are thus the most firmly established features of the frequency spectrum of the daytime pulsations at middle latitudes. They do not, however, lend themselves to an interpretation in terms of a harmonic series of resonant periods. They have thus become quite unfashionable in recent years and are often conveniently forgotten.

The two peaks corresponding to terms 4 and 7 of the geometric progressions of Figures 6 and 7 are the most prominent features

of the spectra of the two afternoon data samples; they also correspond to the two peaks reported in the earlier studies. The greater period range covered in the present work, combined with the improved recording and analysis techniques that have become available in recent years, permits the identification of the two peaks as terms in the geometric progression. With the exceptions of numbers 4 and 7, none of the terms of the progression appear as really outstanding peaks in the amplitude curves; terms 1 and 2 do, however, appear quite clearly in the period distribution of Figure 6. The data for the 3-hour sample on 19 January 1979 (Figure 7) would not, if considered alone, be recognized as a geometric progression of peaks. The elements of the progression become discernable once such an interpretation is suggested. It is only when the data are separated into 15-minute intervals in Figures 8 and 9, however, that the individual peaks in the progression become clearly evident.

In view of the nature of the data shown in Figures 6 through 9 and the lack of any theoretical reason to expect a geometric progression, it is not too surprising that such a progression has not previously been reported. Careful analysis was required to disclose the peaks in the progression with the exception of the two prominant peaks which were previously reported. It was only the confidence engendered by the results of the analysis of the 18 April 1965 data (JGR referees notwithstanding) that motivated the successful development of the modified analysis technique which produced the later results.

Much of the variability in the data can be attributed to the low Q's of the resonances, but it seems likely that some of the

variability is due to short-term variations in the spectrum of the source of excitation energy. The suggestion of Holmberg (1951) has been tested by passing random noise through digital filters. When filter bandwidths comparable to those of Figure 1a were used, period distributions similar to those shown in the figure were obtained. In other respects, however, the similarities to the pulsations were slight or non-existent. The filtered random noise waveforms had only a superficial resemblance to those of the pulsations. As the center period of the filter passband was shifted, no occurrences of superposed wavetrains of different periods were observed, and none were expected. In the case of the pulsations, the occurrences of superposition were essential to the hypothesis of a natural band structure produced by magnetospheric resonances prior to the analysis. Also for the random noise, the period distributions were determined solely by the filters and always peaked near the centers of the passbands as would be expected. No strong trends of clockwise or counter-clockwise polarization such as those shown in Figure 3 were found in the polarization traces obtained from the random noise. The simple hypothesis of Holmberg thus requires modification, probably in the assumption of truly random noise as the source of excitation energy.

Fernando and Kannangara (1966) found two peaks at 38 and 60 seconds in the period distribution of the pulsations at Colombo (-3° geomagnetic latitude). The period ratio of 1.58 suggests that the peaks are terms in a geometric progression. They might also, of course, be the second and third harmonics of a harmonic series with a fundamental period of about 120 seconds. An analysis

covering a wider period range would be required to settle this point. Mainstone (1967) published sonograms from Esk (-37° geomagnetic latitude) and Cougar Mountain ($+54^{\circ}$) showing three resonances whose periods had ratios of roughly 1:2:3; the longest period was about 50 seconds. The periods were not sufficiently well defined to distinguish between a geometric progression with a common ratio somewhat less than 2 or a harmonic series with a fundamental period of about 50 seconds. A fourth resonance in the Pc5 period range was inadequately observed because of instrumentation limitations. This casts doubt on the interpretation of a harmonic series with a 50 second fundamental period. Averaged power spectra from New Jersey ($+49.5^{\circ}$ geomagnetic latitude) reported by Herron (1967) and Davidson (1964) show a prominent peak at about 20 seconds. The other peaks in the 40 to 500 second period range are less pronounced and do not appear to support either a geometric or harmonic progression. The averaging of the data over all 24 hours of the day and over a 3-month interval may have obscured some patterns that would have appeared in shorter time intervals.

Stuart et al. (1971) produced power spectra of pulsations recorded at three U.K observatories for 70- and 90-minute intervals. Of 80 reliable sets of spectra, about 25% were judged to be "too complex for interpretation". Other spectra could be interpreted in terms of harmonic series whose fundamental periods were not observed. A consistent pattern for all three of the rather closely spaced stations was not observed, however, and quite complicated assumptions were necessary for the interpretation of the

results. The Q's indicated by the spectra are considerably higher than would be expected at those stations from the results of Holmberg (1951) and Stuart and Usher (1966); other studies, including the present one, also indicate low Q's for the pulsations. The spectra are also in disagreement with the two peaks observed by Holmberg (1951) at Eskdalemuir, one of the stations used by Stuart et al. (1971).

Although power spectrum analysis has often been applied to the pulsations, no other observations of harmonic series of resonances at middle latitudes have been reported. A rather extensive survey of data from the Air Force Geophysics Laboratory's stations utilized power spectrum analysis in an unsuccessful search for evidence of harmonic series (McClay, 1978, private communication).

IV. D. SATELLITE OBSERVATIONS

A harmonic series of resonant pulsation periods with a fundamental period of about 100 seconds has recently been observed at the ATS-6 satellite in geosynchronous orbit at about 6.5 R_E (Takahashi and McPherron, 1982). The "harmonic events" are reported to be a common feature of the pulsation data.

Many other satellite observations of pulsations have been reported. The pulsations usually exhibit low-Q waveforms comparable to those observed at the surface. The reports of isolated events do not, therefore, provide any reliable information on the nature of possible resonance phenomena. In the few instances in which somewhat larger data samples were used, the analyses did not yield any definitive results.

An unusual high-Q event comprised of pulsations of four different periods was observed at the ATS-1 satellite in synchronous orbit during a magnetic disturbance on 7 May 1967 by Barfield et al. (1972). If the resonances were indeed as sharp as indicated by the wavetrains shown, this single event would provide good estimates of the true resonant periods. Power spectral analysis of a time interval which included some lower-Q activity in addition to the high-Q wavetrains yielded periods of 182.9, 98.5, 64.0, and 41.3 seconds which were assigned simple harmonic indices of 1, 2, 3, and 5. The frequency ratios of 1:1.86:2.85:4.42 would, however, provide an equally good fit to four consecutive terms of a geometric progression. Periods scaled directly from the three high-Q wavetrains shown yielded frequency ratios of 1:1.75:2.84, which provide a very good fit to a geometric progression with a common ratio of 1.7. The departure from a harmonic series is not large, but the apparent high Q of this event suggests that the departure might be significant.

IV. E. STANDING WAVE OBSERVATIONS

The first conclusive evidence for a magnetospheric origin of hydromagnetic waves was the observation of waves having periods of several minutes which occurred simultaneously at conjugate points (Sugiura, 1961). A number of other observations of the simultaneous occurrence of long-period waves at conjugate points have been reported since. Many of the observations were at high latitudes so that the field lines from the recording stations lay outside the plasmasphere. In at least one instance, however, a wave with a six-minute period was observed inside the plasmasphere (Stuart and Langerotti, 1982).

The conjugate-point observations indicate standing waves (i.e., resonance phenomena) in the magnetosphere and therefore pose two important difficulties for the field-line-resonance hypothesis. First, many of the observed standing-wave periods are much longer than those calculated from present knowledge of plasma densities in the magnetosphere (cf., Stuart and Lanzerotti, 1982). Second, the fundamental periods of the harmonic series provide definite lower limits for the periods which can be accounted for by the field-line-resonance hypothesis. Since many of the observed standing-wave periods are much longer than the fundamental periods indicated by the observations, an additional resonance mechanism would be required to account for the longer periods.

The long periods of the standing waves are not incompatible with the observations of geometric progressions of resonant periods. No theory presently exists for the geometric progressions, so no comparison is possible. The indications are quite strong, however, that present theory requires modifications, in one way or another, to fit the observational data.

V. CONCLUSION

No final conclusions concerning the nature of the magnetospheric resonance mechanisms can be reached until better agreement between the various observations and between the observations and theory is attained.

At present, the observational evidence at the geosynchronous satellite altitude, and presumably at high-latitude ground stations as well, favors a harmonic series with a fundamental period

of about 100 seconds (Takahashi and McPherron, 1982). However, the results of Barfield et al. (1972) are ambiguous, and standing-wave observations indicate resonance phenomena at much longer periods.

At mid-latitudes, the present observational evidence favors geometric progressions of resonant periods. The data presented here, supported by the earlier observations of the two strongest peaks of the daytime period distributions, constitute convincing evidence. The standing-wave observations are compatible with the geometric progressions but not with harmonic series with comparatively short fundamental periods.

Both recording and analysis techniques capable of revealing any resonance phenomena present in the pulsations have now been available for several years. A significant amount of effort is required, as is clear both from the nature of the results to date and from the lack of a larger quantity of useful results. Another essential tool is an open mind as to what the analyses may reveal. Additional analyses of observational data are needed in this important field of research. Now that the work under this grant has been terminated, however, it seems unlikely that all of the essential tools will be brought to bear on the problem in the foreseeable future.

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Figure Captions

Figure 1a. Period Distributions of Pulsations in Bands A4 through A9. The arrows below the plots designated as resonance numbers 1 through 6 form a geometric progression of periods with a common ratio of 1.7. The C's below the plots indicate the nominal cut-off periods of the bandpass filters used in the analysis.

Figure 1b. Period Distributions for Bands A1 through A5 with an Expanded Ordinate Scale. Bands A4 and A5 and arrows 1 and 2 are repeated from Figure 1a. The arrows below Bands A1 through A3 indicate the median periods for those bands; those periods do not form a continuation of the geometric progression of Figure 1a.

Figure 2. Section of a Polarization Trace in the Horizontal (X-Y) Plane. The cumulative azimuth angle obtained from the filtered X and Y waveforms is plotted against time. The durations of four polarization runs are shown.

Figure 3. Polarization Traces in the Horizontal Plane for Bands A1 through A9. The strong clockwise and counter-clockwise trends occurring during the 12-hour interval are clearly displayed; the compressed time scale causes loss of detail. The nominal cut-off periods of the bandpass filters are shown.

Figure 4. Derivation of One of the Peaks of a Composite Period Distribution from the Individual Distributions obtained from Narrow, Overlapping Filter Passbands. Data of 2 May 1978.

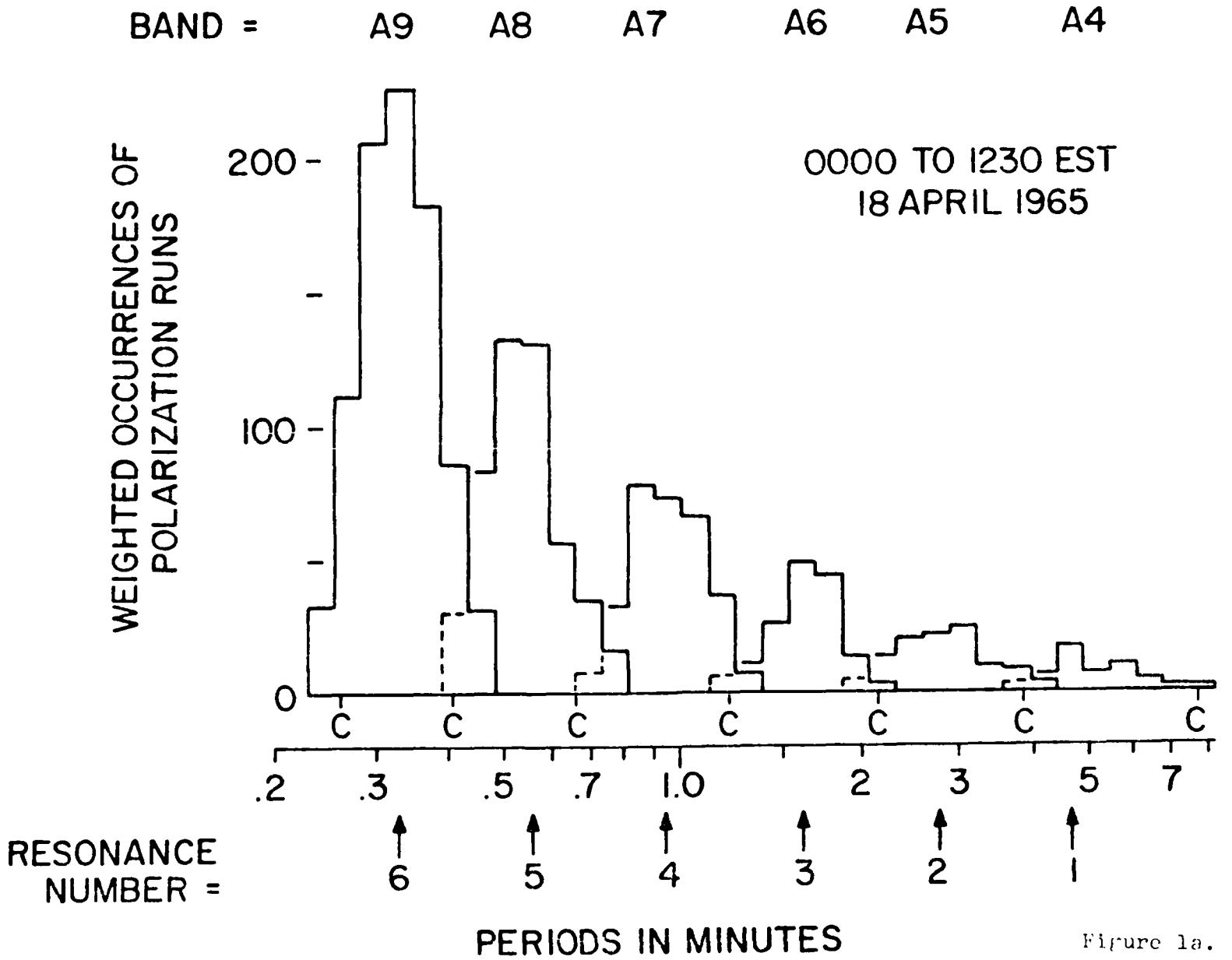
Figure 5. Composite Period Distribution and Average Amplitudes of Pulsations Recorded at Mt. Clemens, Michigan, from 0000 to 0300 GMT on 2 May 1978, Kp = 7o. Vertical dotted lines form a geometric progression with a common ratio of 1.84.

Figure 6. Composite Period Distribution and Average Amplitudes of Pulsations Recorded at Rapid City, South Dakota, from 1300 to 1600 CST on 15 January 1979, Kp = 4o. Vertical dotted lines form a geometric progression with a common ratio of 1.56.

Figure 7. Composite Period Distribution and Average Amplitudes of Pulsations Recorded at Rapid City, South Dakota, from 1200 to 1500 CST on 19 January 1979, Kp = 2+. Vertical dotted lines form a geometric progression with a common ratio of 1.56.

Figure 8. Average Amplitudes of Pulsations for Three of the 15-Minute Intervals of the 3-Hour Data Sample of Figure 7.

Figure 9. Average Amplitudes of Pulsations for Three of the 15-Minute Intervals of the 3-Hour Data Sample of Figure 7.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PERIODS IN MINUTES

Figure 1a.

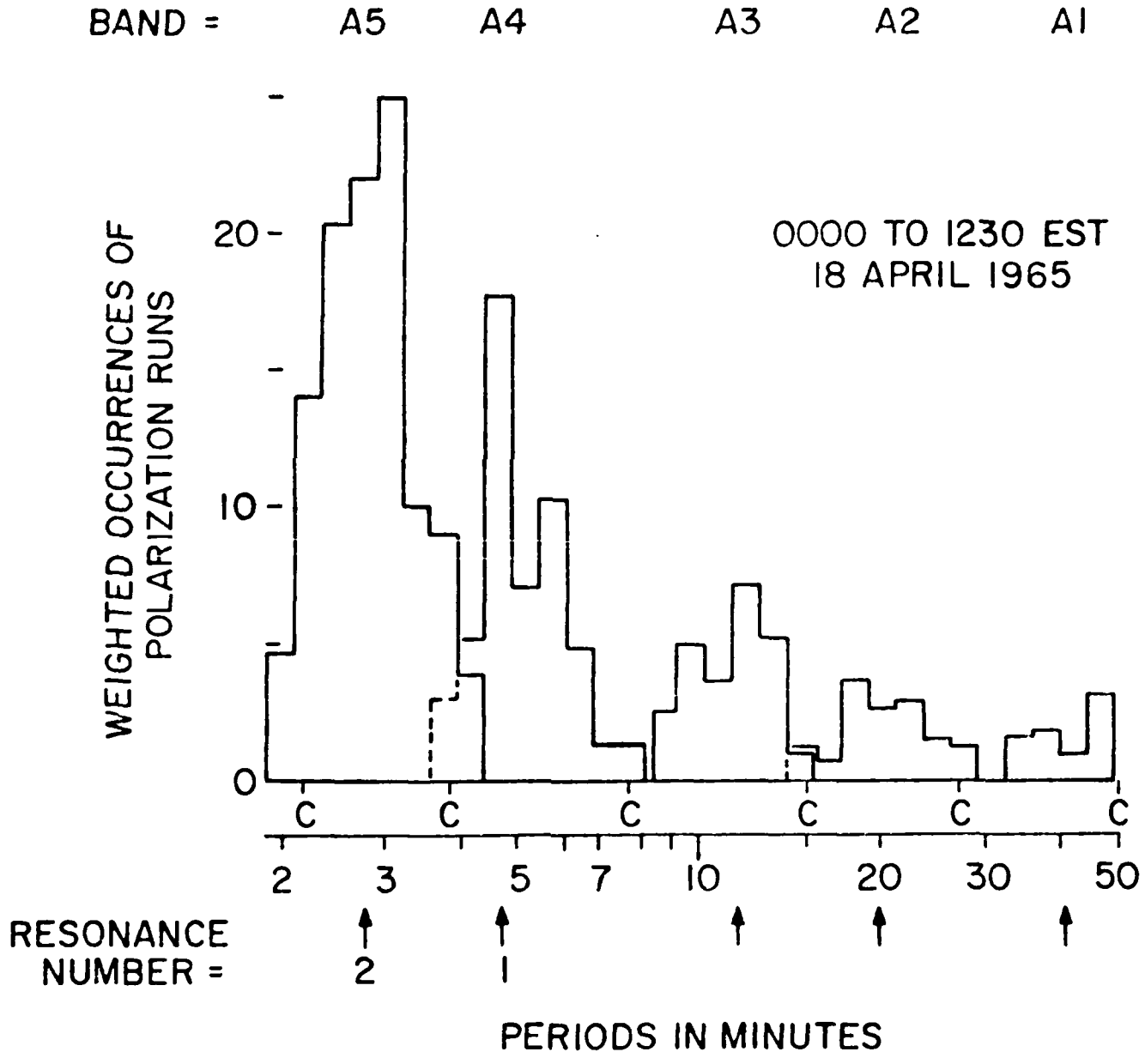
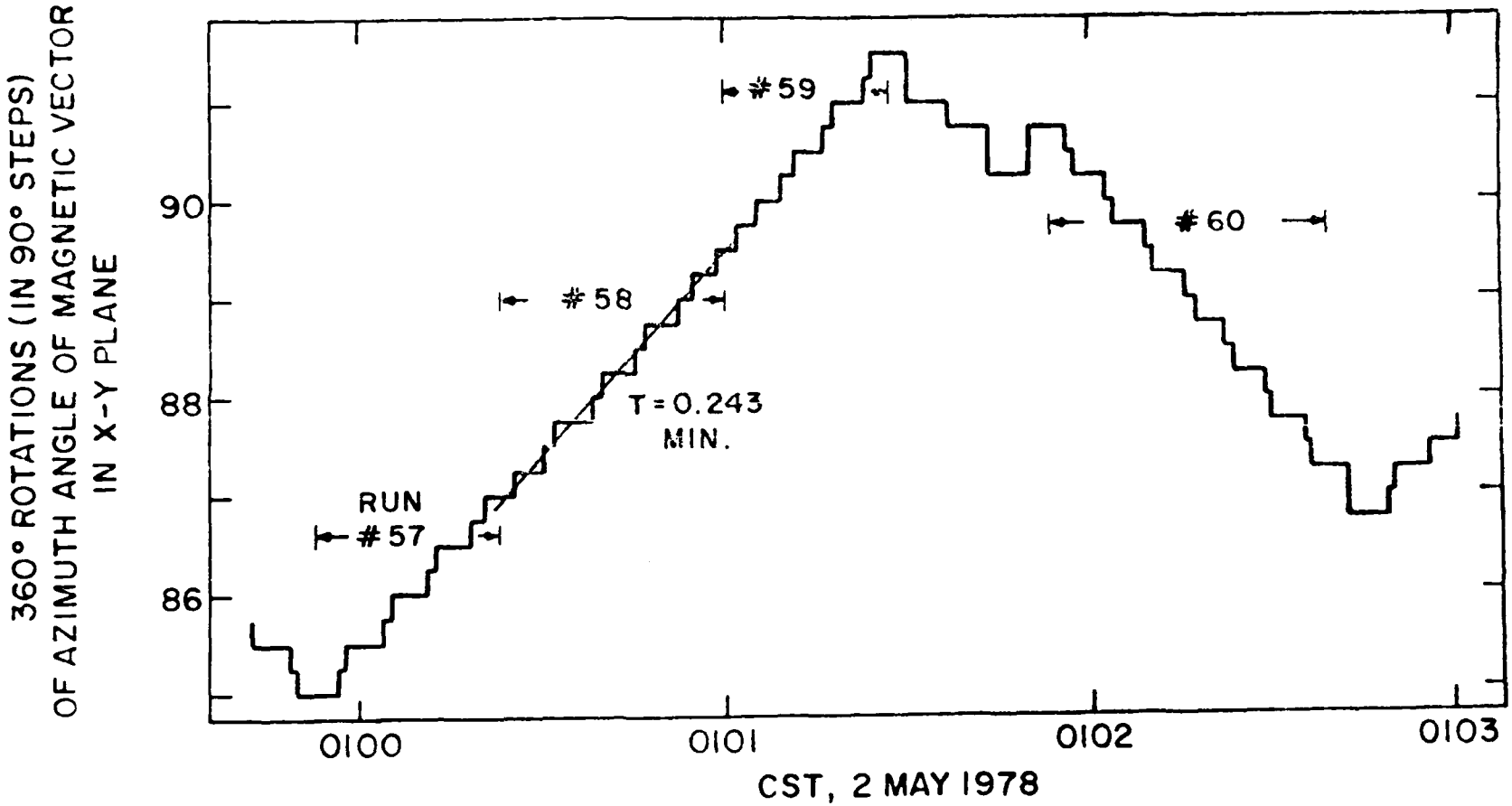

BAND =
A5
A4
A3
A2
A1
WEIGHTED OCCURRENCES OF POLARIZATION RUNS
20
10
0
0000 TO 1230 EST
18 APRIL 1965
C
C
C
C
C
C
2
3
5
7
10
20
30
50
RESONANCE NUMBER =
2
1
PERIODS IN MINUTES

Figure 1b.



SECTION OF POLARIZATION TRACE
FILTER PASSBAND = 0.199 TO 0.273 MINUTES
PULSATIONS RECORDED AT MT. CLEMENS, MICH.

Figure 2.

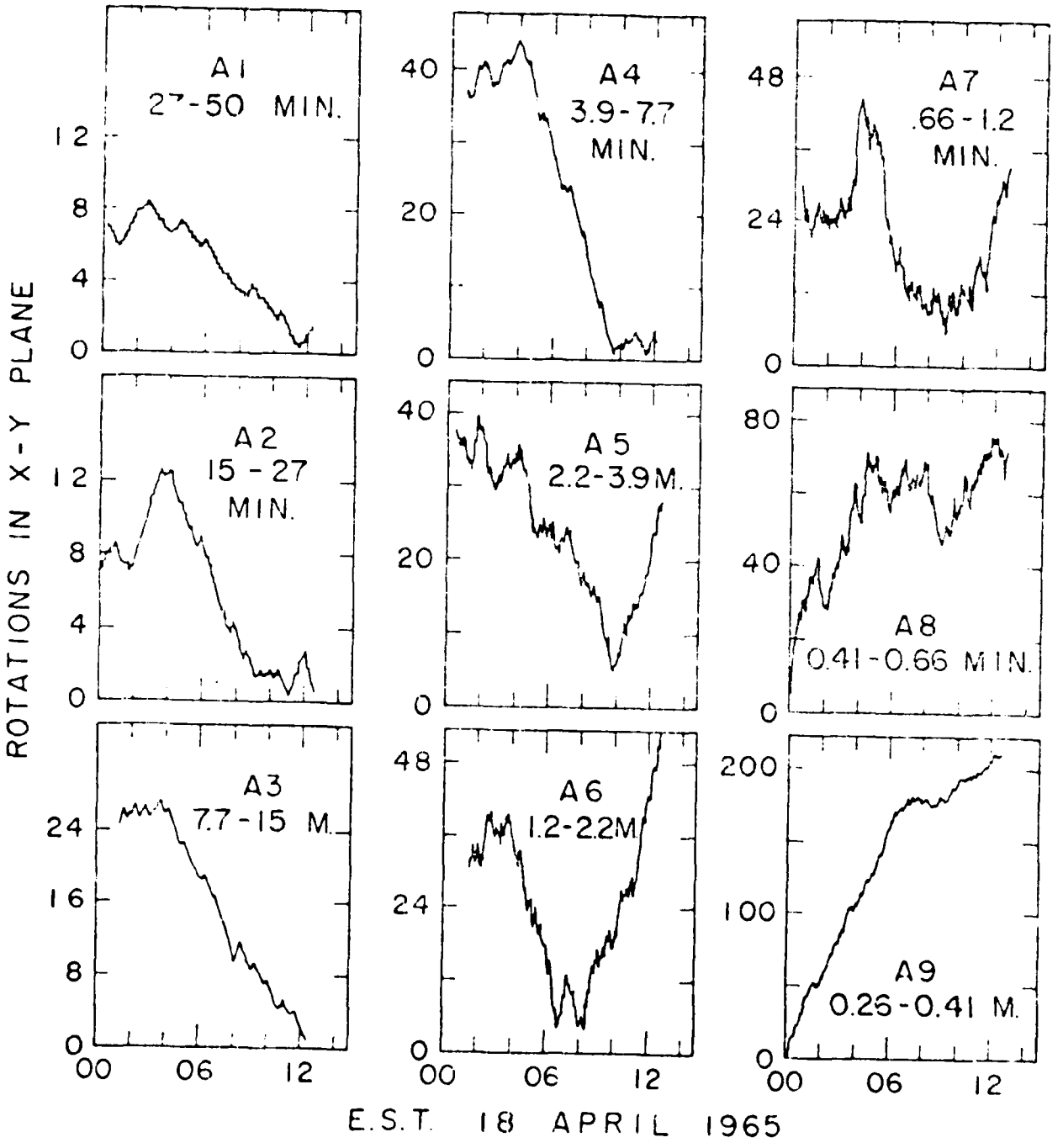
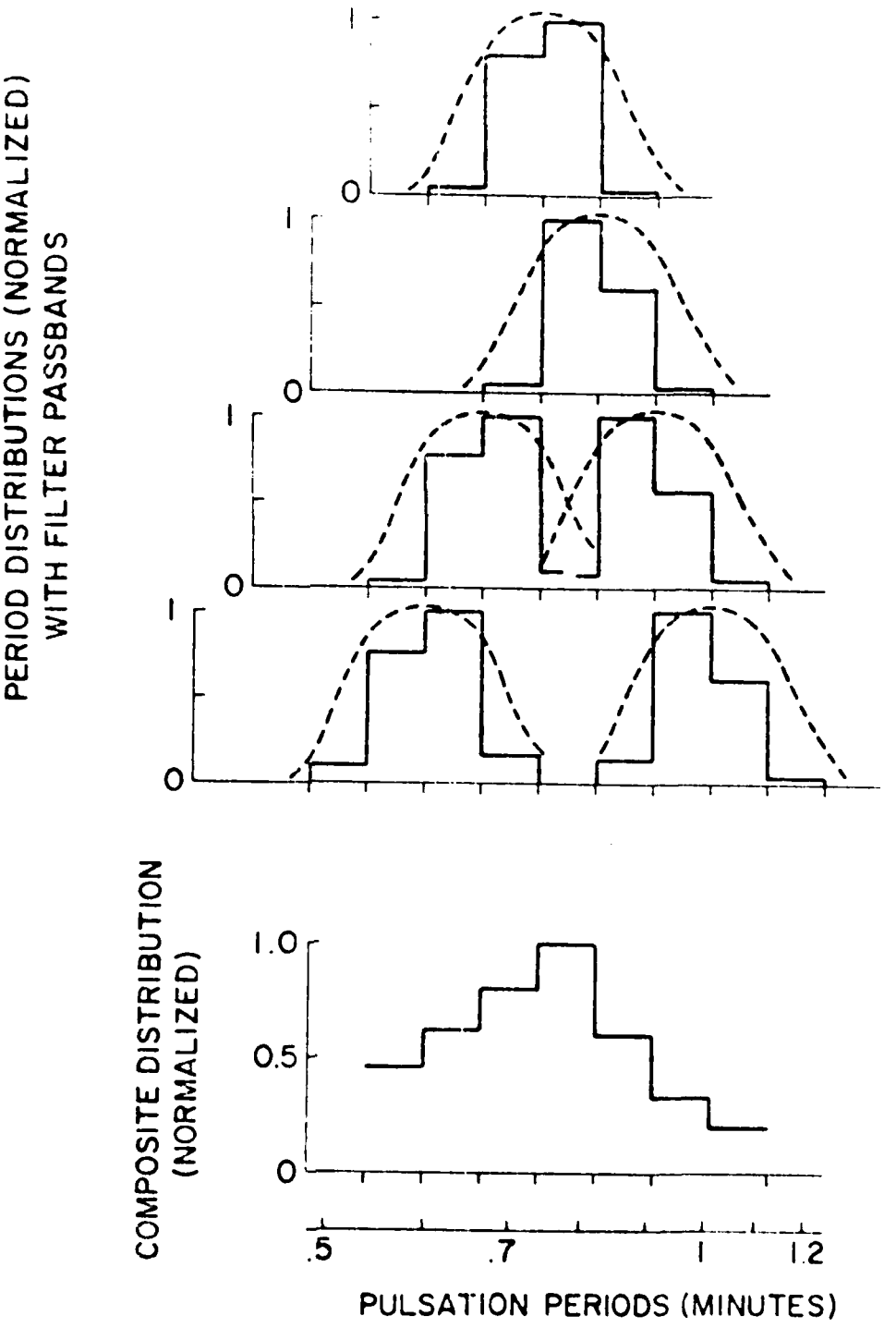

A1
27-50 MIN.
A2
15 - 27
MIN.
A3
7.7 - 15 M.
A4
3.9 - 7.7
MIN.
A5
2.2 - 3.9 M.
A6
1.2 - 2.2 M.
A7
.66 - 1.2
MIN.
A8
0.41 - 0.66 MIN.
A9
0.26 - 0.41 M.
ROTATIONS IN X-Y PLANE
00
06
12
E.S.T. 18 APRIL 1965

Figure 3.



DERIVATION OF COMPOSITE PERIOD DISTRIBUTION

Figure 4.

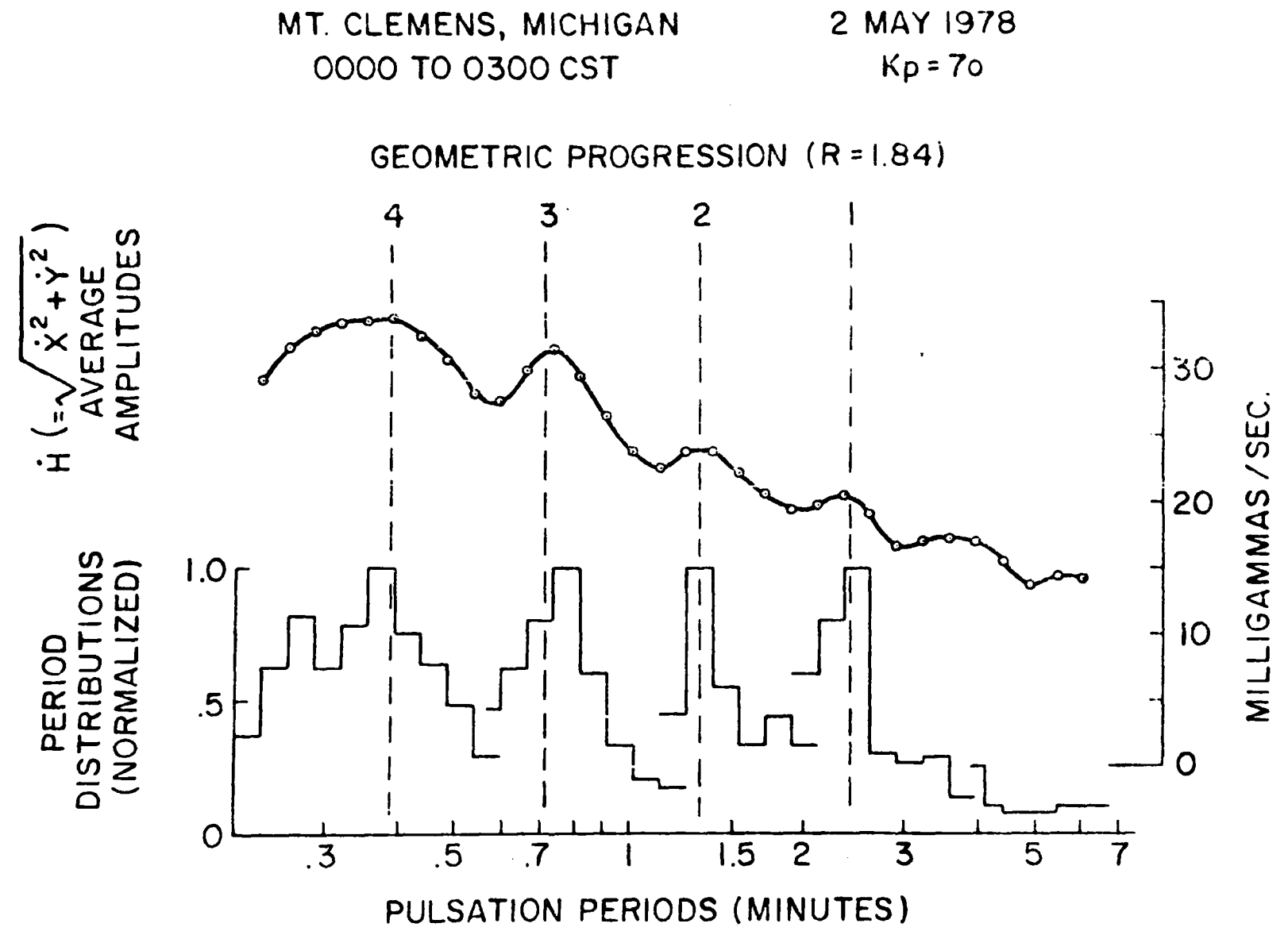

MT. CLEMENS, MICHIGAN
0000 TO 0300 CST
2 MAY 1978
Kp = 7o
GEOMETRIC PROGRESSION (R = 1.84)
4
3
2
1
$\dot{H}\ (=\sqrt{\dot{X}^2+\dot{Y}^2})$ AVERAGE AMPLITUDES
PERIOD DISTRIBUTIONS (NORMALIZED)
1.0
.5
0
30
20
10
0
MILLIGAMMAS/SEC.
.3
.5
.7
1
1.5
2
3
5
7
PULSATION PERIODS (MINUTES)

Figure 5.

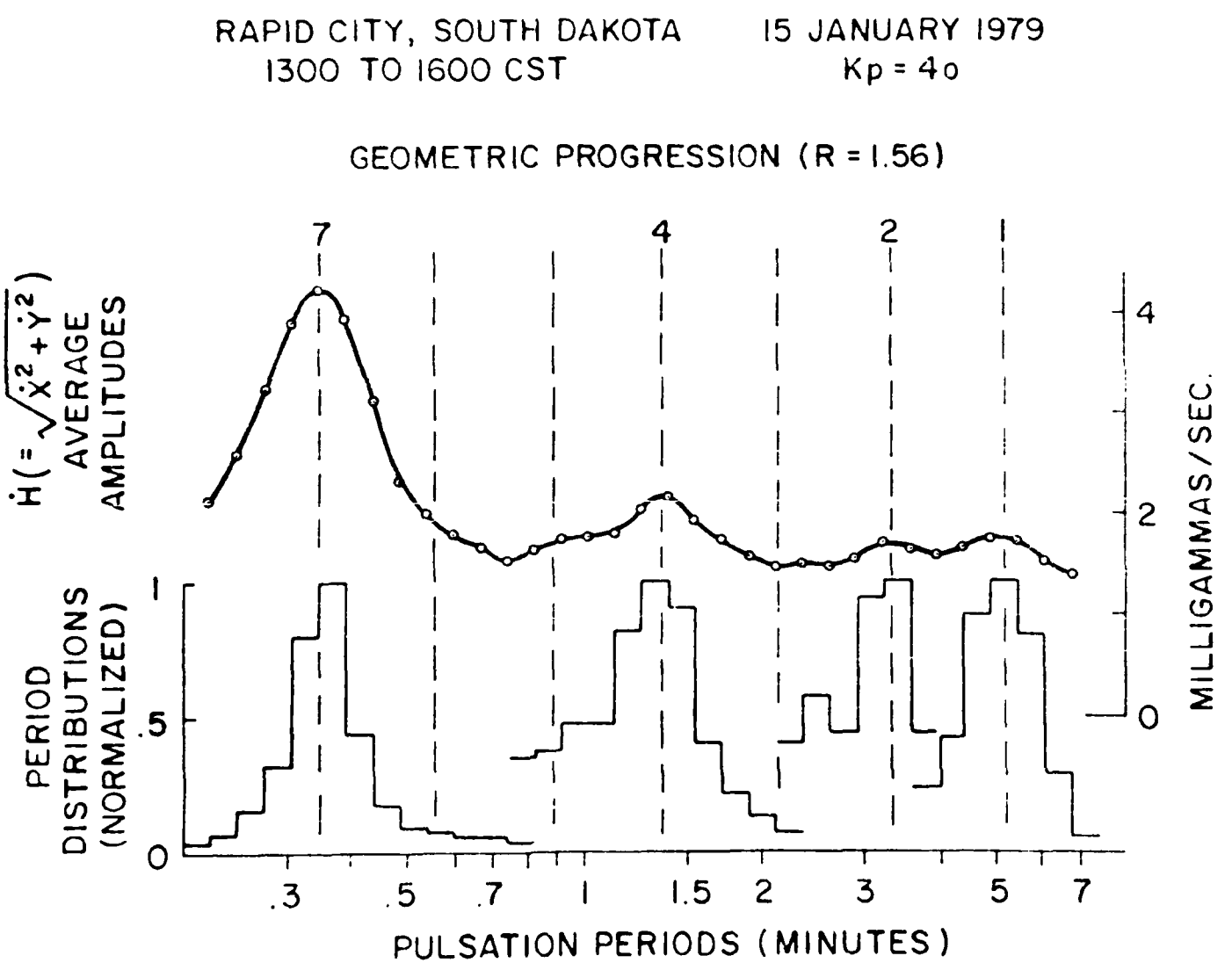

RAPID CITY, SOUTH DAKOTA
1300 TO 1600 CST
15 JANUARY 1979
Kp = 4o
GEOMETRIC PROGRESSION (R = 1.56)
7
4
2
$\dot{H}(=\sqrt{\dot{X}^2+\dot{Y}^2})$ AVERAGE AMPLITUDES
MILLIGAMMAS/SEC.
PERIOD DISTRIBUTIONS (NORMALIZED)
PULSATION PERIODS (MINUTES)
.3
.5
.7
1
1.5
2
3
5
7

Figure 6.

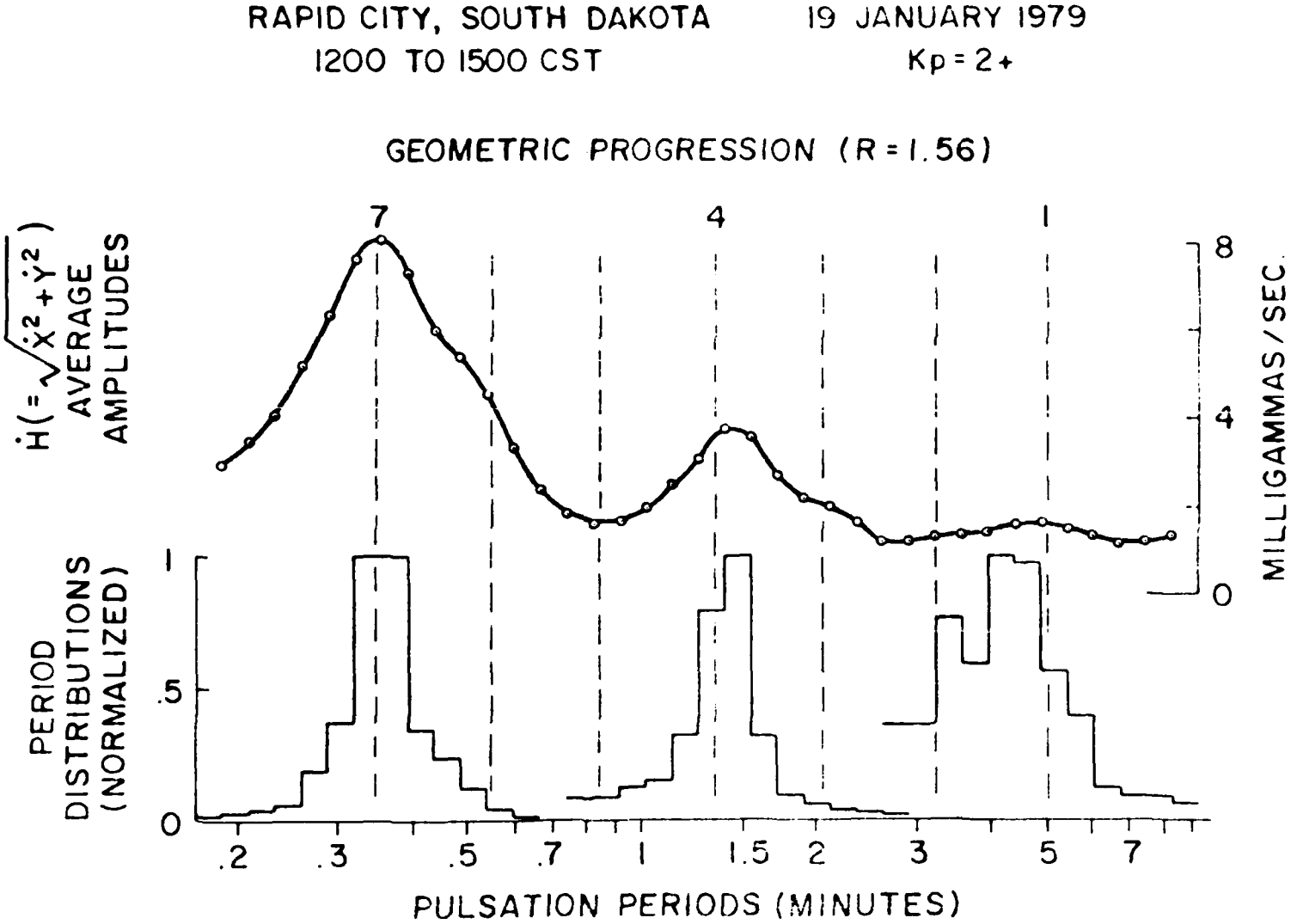

RAPID CITY, SOUTH DAKOTA
1200 TO 1500 CST
19 JANUARY 1979
Kp = 2+
GEOMETRIC PROGRESSION (R = 1.56)
7
4
1
$\dot{H}(=\sqrt{\dot{X}^2+\dot{Y}^2})$ AVERAGE AMPLITUDES
MILLIGAMMAS/SEC
8
4
0
PERIOD DISTRIBUTIONS (NORMALIZED)
1
.5
0
.2
.3
.5
.7
1
1.5
2
3
5
7
PULSATION PERIODS (MINUTES)

Figure 7.

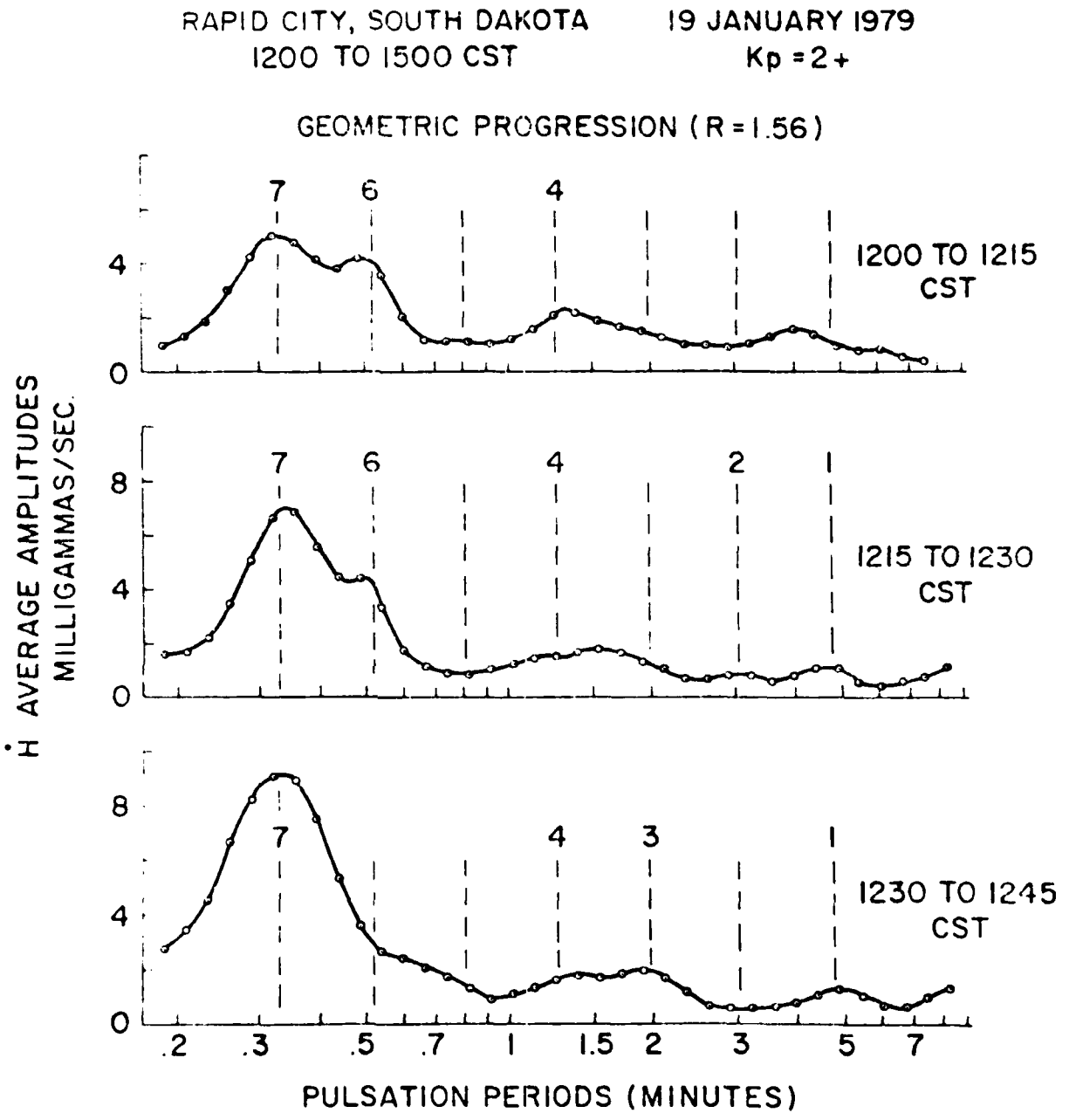

RAPID CITY, SOUTH DAKOTA
1200 TO 1500 CST
19 JANUARY 1979
Kp = 2+
GEOMETRIC PROGRESSION (R = 1.56)
7
6
4
1200 TO 1215 CST
0
4
7
6
4
2
1
1215 TO 1230 CST
0
4
8
7
4
3
1
1230 TO 1245 CST
0
4
8
.2
.3
.5
.7
1
1.5
2
3
5
7
PULSATION PERIODS (MINUTES)
Ḣ AVERAGE AMPLITUDES MILLIGAMMAS/SEC.

Figure 8.

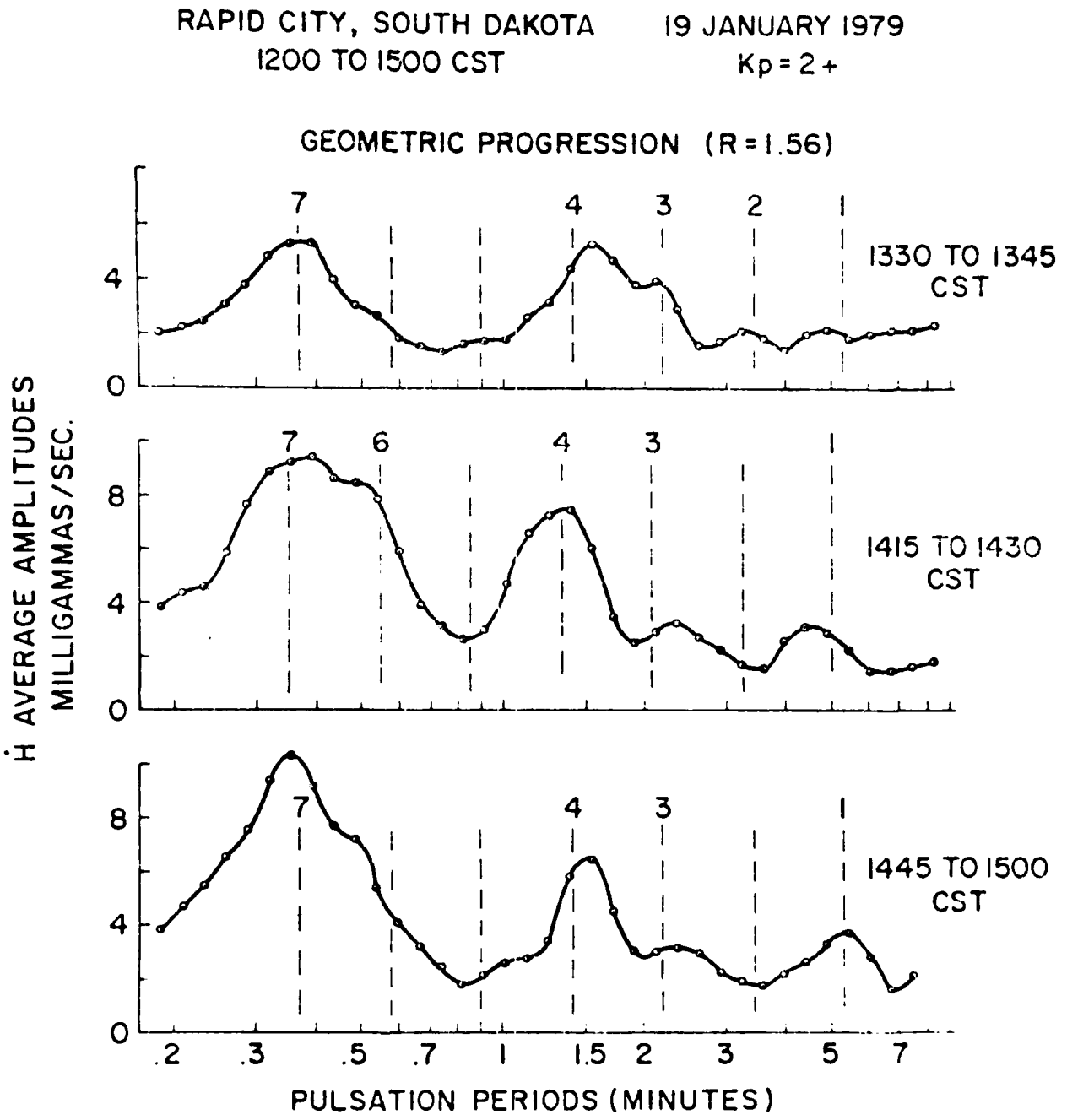

RAPID CITY, SOUTH DAKOTA
1200 TO 1500 CST
19 JANUARY 1979
Kp = 2+
GEOMETRIC PROGRESSION (R = 1.56)
7
4
3
2
1
1330 TO 1345 CST
7
6
4
3
1
1415 TO 1430 CST
7
4
3
1
1445 TO 1500 CST
Ḣ AVERAGE AMPLITUDES MILLIGAMMAS/SEC.
0
4
8
.2
.3
.5
.7
1
1.5
2
3
5
7
PULSATION PERIODS (MINUTES)

Figure 9.

END

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